Reprint from Applied Optics 19, 2088 (July 1980)

# Simple interferometric technique for alignment of segmented retroreflectors

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Received 18 January 1980.

Interferometric techniques are described here for obtaining multiple laser beams that have arbitrarily large spatial separations and are parallel within an angular tolerance corresponding to a small fraction of fringe over the mode diameter. Also described is the use of these beams to align interferometrically a large-aperture segmented retroreflector (SRR). The SRR offsets and retroreflects an incident laser beam so that the reflected beam is parallel to the incident beam within an angular tolerance about the same as that of the multiple beams. That these angular tolerances are achieved is demonstrated by the successful use of the SRRs with beam offsets up to 21 cm to obtain optical Ramsey fringes[1] where the wave fronts of the three beams used in the experiment had to be parallel to much better than $\lambda/2$ over the mode diameter (for details of the optical Ramsey fringe techniques see Refs. 2–5).

The configurations of the SRRs discussed here are determined by the arrangement of laser beams needed for these Ramsey fringe experiments. This arrangement of three equally spaced parallel standing-wave beams is formed from the input beam by using two opposing SRRs. One is constructed as indicated in the upper part of Fig. 1. In a three-zone Ramsey experiment, a second SRR is used that is similar but is made without a cat's-eye and has half the spacing of input and reflected beams. The input plane wave laser beam enters the first SRR at position *1* in Fig. 1 and is retroreflected by it to position *3*. The beam is then retroreflected by the opposing SRR from position *3* to position *2*, where it enters the cat's-eye of the first SRR. The beam is then retroreflected back around the optical circuit by the cat's-eye to produce the three standing-wave beams. The reflecting surfaces of the SRRs must be interferometrically aligned to obtain the required parallelism between input and reflected beams. In previous work,[4,5] the three beams with small spacings were obtained with two opposing cat's-eyes. The SRRs discussed here have been developed to produce large beam spacings, up to a few meters; cat's-eyes with such large-aperture aberration-free optics would be difficult to construct and would have undesirably large dimensions.

The first step in the interferometric alignment procedure is to obtain parallel laser beams (three in this case) with the desired spacing. These are then used to align the components of the SSRs. The experimental setup is indicated in Fig. 1. All components are mounted on a rigid tabletop. The components for obtaining the parallel beams are the input beam and small reference mirror *rm*, both fixed with respect to the table, and a modified Michelson interometer *MMI*, which can be translated parallel to the input beam. The input beam, from a red He-Ne laser *l*, passes through optical isolator *i* and beam-expanding telescope *t*, which produces a plane wave of the desired mode diameter (~1 cm in this case). The interferometer *MMI* consists of flat beam splitters $S_1$, $S_2$, and $S_3$ (one for each desired beam, positioned to give the desired beam spacing), flat beam splitting end mirror $S_4$, flat beam splitter $S_5$, mercury reference mirror *Hgm*, and cat's-eye retroreflecting end mirror $ce_1$ (adjusted to give a plane reflected wave). Beam splitter $S_5$ reflects a beam vertically down to mercury mirror *Hgm*, which forms a reflecting surface always in the horizontal plane. The Michelson components are mounted on a separate rigid platform that can be translated (without changing the mirror adjustment) and rotated about the three orthogonal axes.

The interferometer is of the Michelson type but modified by replacing the plane end mirror in one of the arms with the retroreflecting cat's-eye. This destroys the symmetry of reflections from the two arms and thereby greatly increases the sensitivity to relative changes of the angles between the input beam, the reflected beam, and the interferometer axis. This is seen from the following consideration. If the interferometer platform is rotated by angle $\theta$, the angle of reflection from one arm changes by $\theta$ and that from the other by $-\theta$, resulting in localized fringes corresponding to the wedge $2\theta$. In contrast, for the normal Michelson with two flat end mirrors, the rotation would produce equal angles of reflection for the two arms, resulting in the relatively angle-insensitive circular fringe pattern. A fixed angular position of the Michelson platform is obtained by adjusting beam splitters $S_1$, $S_4$, and $S_5$ to give two uniform-intensity fringe systems at observation point $o_1$ in Fig. 1. These systems are formed by interference of the beams reflected from cat's-eye $ce_1$ and beam splitter $S_4$ and from $ce_1$ and horizontal reference mirror *Hgm*. The first system specifies the platform rotation about the two orthogonal axes perpendicular to the input laser beam, while the second specifies the rotation about the third orthogonal axis, that of the input laser beam. After these adjustments, the platform can be rotated, giving line fringes, and then returned to the original angular position by rotating the platform until the two uniform-intensity fringe systems are again obtained.

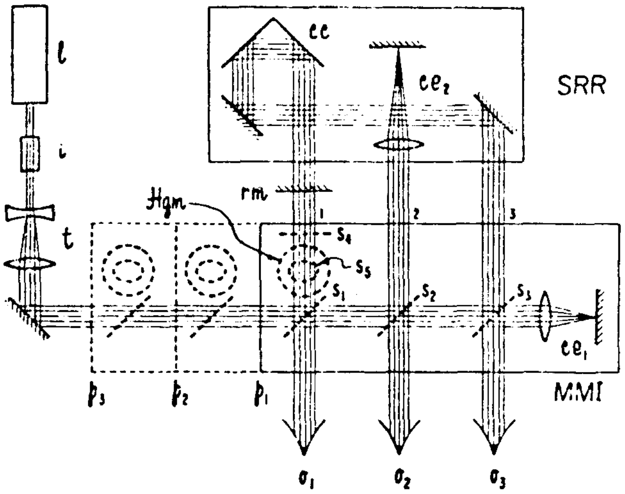

Fig. 1. Experimental setup for interferometric alignment of modified Michelson interferometer (*MMI*) and segmented retroreflector (*SRR*). See text for explanation of components.

The angular sensitivity of this rotation is determined by the minimum detectable nonuniformity of the fringe intensity. It is probably reasonable to assume that $1/5$ fringe nonuniformity can be observed visually, corresponding to an angular sensitivity for the platform rotation of $1/10$ fringe across the laser beam diameter. For the 1-cm beam diam used here, this gives a sensitivity of $\delta\theta = 3 \times 10^{-6}$ rad. The sensitivity could be greatly improved by using diodes to detect the intensity at three points of the approximately uniform fringe and always rotating the platform to give equal signals at the three points. The residual angular deviation between settings would then be determined by the SNR achieved. This modified Michelson interferometer, with its high sensitivity to angular position, is the key for obtaining the three laser beams with arbitrarily large separations and with wave fronts parallel to a small fraction of a fringe over the mode diameter.

The three output beams of the interferometer are made parallel by aligning all three normal to fixed reference mirror *rm* as follows. With the Michelson platform in position $p_1$ in Fig. 1, beam splitters $S_1$, $S_4$, and $S_5$ are adjusted, as discussed above, to give the two uniform fringe systems at $o_1$. Then reference mirror *rm* is placed in position to retroreflect output beam *1* and rotated until a uniform fringe is obtained at $o_1$ for the interference between the beams reflected from *rm* and $S_4$ (and, simultaneously, those from *rm* and $ce_1$). Output beam *1* is now normal to the reference mirror within the angular sensitivity $\delta\theta$. The reference mirror at this angle is used for alignment of output beams *2* and *3*.

To align beam 2, the Michelson platform and mercury mirror *Hgm* are translated to position $p_2$ (without changing the adjustment of $S_1$, $S_4$, or $S_5$) where beam 2 is incident on the reference mirror. The platform is rotated to give the two uniform fringe systems at translated observation point $o_1$. Since the surface of mercury reference mirror *Hgm* always lies in the horizontal plane, this rotation ensures that the angle of beam *1* is the same as for platform position $p_1$ within $\delta\theta$ (i.e., normal to the reference mirror). By now rotating beam splitter $S_2$ to give a uniform fringe at $o_2$, beam *2* is made normal to the reference mirror within $\delta\theta$ and parallel to beam *1* within $\sim\sqrt{2}\delta\theta$. By translating the platform to $p_3$, beam *3* is made parallel to beam *1* with the same procedure. In this way, three plane wave laser beams are obtained with all the wave fronts parallel within $\sim\sqrt{3}\delta\theta$. With the reference mirror removed, these beams can now be used for alignment of the SRR.

The SRR, indicated in the upper part of Fig. 1, consists of a corner cube *cc* to give retroreflection, two 45° mirrors (one adjustable in angle) to translate the retroreflected beam to position *3*, and a small cat's-eye to retroreflect beam *2*. (The corner cube could be replaced by a small cat's-eye, eliminating the undesirable elliptical polarization that can be introduced by corner cubes.) A mechanically stable structure is obtained by mounting the corner cube and the adjacent 45° mirror on an Al block, the cat's-eye on a second, and the other 45° mirror on a third, with the blocks rigidly mounted on ~3-cm diam Invar rods. The blocks can be translated on the rods to obtain the desired spacing for the three laser beams. The structure is supported on three screws to allow height and tilt adjustments. To obtain long-term mechanical stability, most of the optical components are epoxied to the blocks. The final angular adjustment is made by compressing three metal–metal contact points on the mount for the 45° adjustable mirror.

For interferometric alignment, the SRR is placed in the position indicated in Fig. 1 to give superposition of the reflected and input beams. Various fringe systems can now be observed at $o_1$, $o_2$, and $o_3$ due to the several possible paths of all the beams. By rotation of the adjustable 45° mirror in the SRR, with beam *2* blocked, all the fringe systems at $o_1$ (six systems) and $o_3$ (one system) can be made to have uniform intensity simultaneously. This condition ensures that an input plane wave at *1* is retroreflected at *3* as a plane wave parallel to the input beam within $\sim\sqrt{2}\delta\theta$. With beams *1* and *3* blocked, the focus of cat's-eye $ce_2$ can be adjusted to give a uniform-intensity fringe system at $o_2$. The retroreflected beam 2 is now plane and is parallel to input beam 2 within $\delta\theta$. The second SRR, without a cat's-eye and with half the input-reflected beam separation, is similarly adjusted using the adjacent beam pairs *1,2* or *2,3*.

The maximum deviation from parallelism for the system of three beams formed by the two opposing SRRs in the Ramsey fringe configuration is probably close to $\sqrt{3}\delta\theta$, since for each angular adjustment the deviation is $\delta\theta$ and there is the equivalent of a maximum of three such adjustments for the total beam path through the combined SRRs. The important parameter for obtaining Ramsey fringes is the fractional fringe deviation across the laser beam rather than the angular deviation. Thus, it is advantageous to use a mode diameter for alignment that is larger than that used in the Ramsey experiment, the fractional fringe deviation being reduced by the ratio of the diameters.

An additional condition imposed on the three laser beams when used to obtain Ramsey fringes should be mentioned briefly. Changes in the relative optical phases as seen by atoms passing through the three beams must be less than $\pi$ during the period of observation. Retroreflection of central beam *2* to produce the standing waves causes this condition to be satisfied if the separation of the SRRs changes due to, for example, mechanical vibrations (just as in the case of two opposing cat's-eyes[4]). With thermal drifts of the SRRs, however, the optical paths of beam 2 and of the offset beam change differently within the SRR, and this produces changes in the relative phases. Thus it would be desirable to reduce thermal drifts by making the SRR mounting blocks from Invar; however, even with the aluminum blocks used here, relative phase changes of $<\pi$ over periods of several hours have been achieved for a beam offset of 21 cm by placing each reflector in a nearly airtight insulating box.

The offset distances of parallel laser beams obtained with the interferometric alignment techniques described here can in principle be arbitrarily large. The upper limit should be reached when the lengths of the Michelson interferometer and SRR become so large that problems of mechanical vibration and distortion can no longer be controlled. Since the optical components are small, the physical dimensions in the direction transverse to the offset can be kept small. The resulting small volume and weight facilitate thermal and mechanical shielding so that construction of interferometrically aligned SRRs with offsets as large as a few meters should be possible. The use of these in Ramsey fringe experiments should result in much higher spectral resolution than has been obtained to date.

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